A Codified Procedure to Assess Resilience in Irrigation Systems Based on Loop Polarity Analysis

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***Abstract*— Agricultural systems are complex systems, whose study requires approaches capable of recognizing the inherent feedbacks between people`s behavior, incentives, and environmental outcomes. Although several studies deal with agricultural systems from that perspective, there are comparatively few that study irrigation schemes based on the feedback effects that may threaten their sustainability. This paper uses feedback loop polarity analysis to build an algorithm to predict irrigation systems` resilience tipping points. It concludes by suggesting that the basic ideas presented might be useful to build operational early warning signals for critical transitions in irrigation systems and in a wider range of systems where tipping points are suspected to exist.**

Keywords-irrigation systems; sustainability; resilience; system dynamics; loop polarity analysis.

I. INTRODUCTION

As defined by Holling [6], ecological resilience refers to the ability to absorb change and disturbance and still maintain the same relationships that control a system's behavior. Nonetheless, the literature is still unclear on how to measure resilience in different systems and therefore on how well that concept translates in practice to analyzing the vulnerability of social systems more broadly [2]. As we cannot hope to manage what we do not even measure, the issue of measurement seems critical for the progress of the research on the field. This paper aims at contributing to bridge that gap by proposing a codified procedure, based on loop polarity analysis [1], for identifying in advance irrigation systems` resilience thresholds.

There are comparatively few works focusing on factors that can threaten the sustainability of irrigation systems [4]. Most of them show that irrigation projects can cause catchment degradation but are also (more often than not) their victims [8]. The most obvious consequence of catchment deterioration by irrigation is erosion, leading to siltation of canals and of reservoirs. This makes poor operation and maintenance (O&M) the bigger problem for the sustainability of irrigation projects mainly in less developed countries where many of those projects are managed for incompetent bureaucracies combined with weak irrigator associations. Causality above can also manifest in reverse, because farmers may simply be unable to carry out maintenance expenses, for being caught in feedback reinforcing loops of inadequate maintenance. Elinor Ostrom [10: p.89] puts the question as follows.

"Unless farmers pay the fees used to hire O&M staff or they perform these O&M activities themselves, many irrigation agencies will not be able to do anything more than operate systems in a minimal fashion. Little investment can be made in routine or emergency maintenance. The initial lack of maintenance triggers a vicious circle that has been characteristic of many large systems constructed in recent years. Without adequate maintenance, system reliability begins to deteriorate. As reliability diminishes, farmers are less willing to make investments in expensive seeds and fertilizers that are of little benefit without a reliable water supply. Without these input investments, the net return from irrigated agriculture declines. As returns fall, farmers become still more resistant to contributing to the system`s sustainability."

This paper indicates how to identify in advance the critical points beyond which, due to the action of vicious feedback loops, irrigation systems lose resilience when hit by even tiny, and so hard to notice, environmental shocks. The remainder of the paper is organized as follows. Section II presents a hypothetical system dynamics model that underpins the above conclusion and summarizes the essence of the loop polarity analysis approach. Section III presents a codified procedure for computing resilience tipping points of irrigation systems. Sections IV and V, respectively, present and discuss the main results of simulation, suggesting how to identify leverage intervention points in collapsing irrigation systems. Section VI concludes by suggesting that the basic ideas presented might be useful to build operational early warning signals for critical transitions not only in irrigation systems, but in a wider range of systems, where tipping points are suspected to exist.

II. THE MODEL

Professor Ostrom`s ideas on the sustainability of irrigation systems outlined in the introductory section were later formalized in a system dynamics model by herself and colleagues at Indiana University [13], which we synthesize in Figure 1.

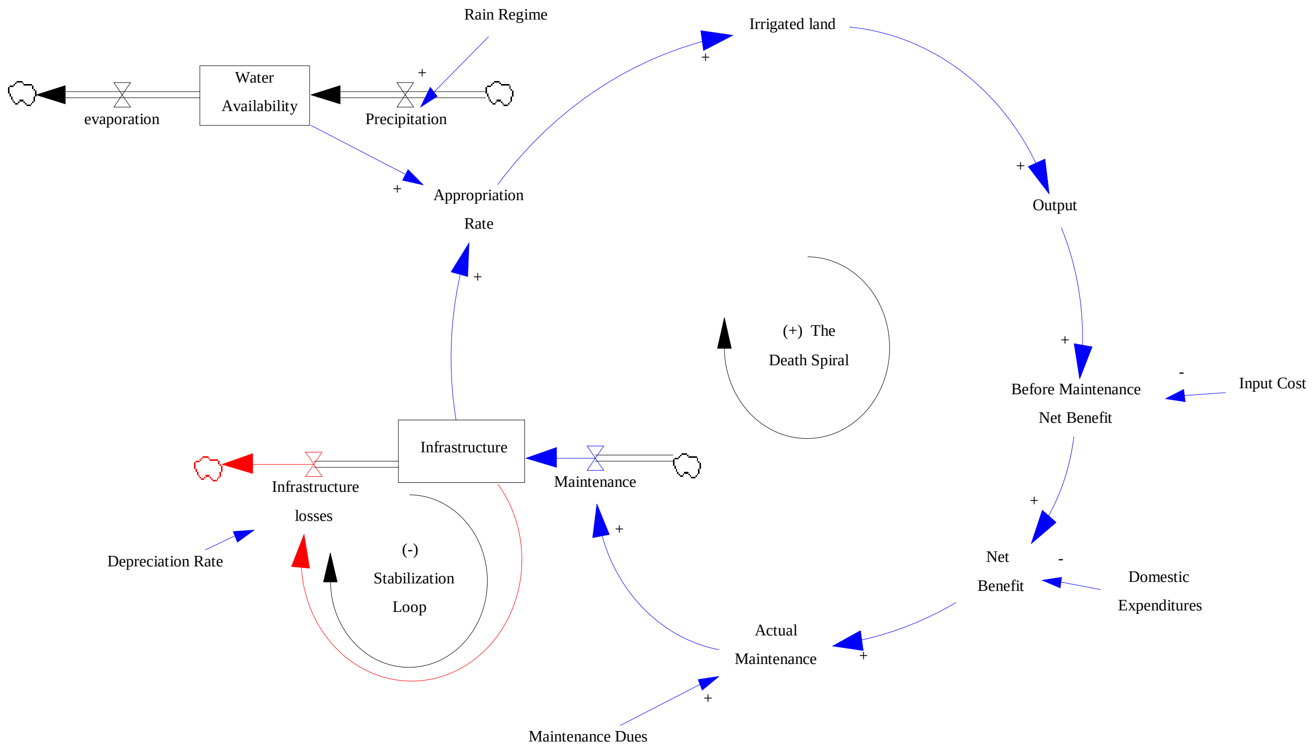


Figure 1. Loop polarity in irrigation projects.

The fully documented original Stella version model is presented in the referred paper and the present VENSIM version is available upon request. In the basic stock-flow structure of the simplified model, there are just two loops. In the self-reinforcing loop labeled as “the death spiral”, the deterioration of the irrigation infrastructure due to inadequate maintenance leads to falling output, benefits and infrastructure maintenance, which further decreases the infrastructure reliability. In the stabilization loop, decreases in the depreciation flow due to the reduction in the state. The time path of the value of the infrastructure is then given by the following differential equation:

dInfrastructure/dt = Maintenance – Infrastructure Losses (1)

where:

Maintenance = min (Maintenance Dues, net Benefit) (2)

Net Benefit = Before Maintenance Net Benefit – Domestic Expenditures (3)

and

Infrastructure Losses = Infrastructure * Depreciation Rate (4)

Disturbances like changes in rain regime are modeled as follows.

Rain Regime = Mean Precipitation Level - PULSE(y, t)* R (5)

where R is the change in the precipitation level starting in year y and lasting for t years.

The degree of resilience of the above system can be assessed as follows: what level of disturbance, droughts for instance, can the system withstand before the agents stop investing the total amount needed for the integral maintenance of the infrastructure?

It is easy to see that as far as irrigators are able to pay maintenance fees the infrastructure is maintained in appropriated use conditions. But if they are forced to spend less than that value, the maintenance rate will be lower than infrastructure losses and the infrastructure will decrease in size. Hence, in the next period, the amount appropriated of water, output and profits will decrease and so do maintenance spending. Once the irrigators are forced to pay less than the right maintenance dues, the system can enter into a snow-ball trajectory we have labeled “the death spiral”, because the final outcome of the process is the complete deterioration of the existing infrastructure. Figure 2 presents the argument graphically. In the following sections, we indicate how to calculate resilience tipping points of irrigation systems.

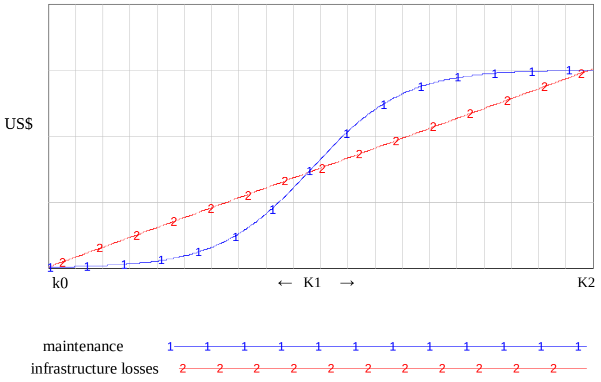


Figure 2. Maintenance and infrastructure losses: k is the value of the infrastucture at time t and k1, its resilience tipping point. Below that point, the death spiral dominates (maintenance<infrastructure losses) and the system collapses to k0, while above it the stabilization loop dominates the system`s dynamics and it will recover its former operation conditions (k2).

III. METHODOLOGY

A more rigorous analysis for how important dynamic patterns arise in social ecological from feedback structures can be found in the classical Richardson’s [11] paper on loop dominance, on which this paper is based.

According to Richardson, the polarity of a single feedback loop involving a single level x and an inflow rate $\dot{x}$ = dx/dt is defined by sign $\left(\frac{d\dot{x}}{dx}\right)$, which is consistent with a more intuitive characterization as follows. The denominator of the fraction – dx – can be thought of as a small change in x, for instance a small change in fish caught in a particular fishery, which is traced around the loop until it results in a small change - $d\dot{x}$ — in the inflow rate, say in the regeneration rate of the system, $\dot{x} = \frac{dx}{dt}$. If the change in the rate, $d\dot{x}$, is in the same direction as the change in the level, dx, then they have the same sign. As $\dot{x}$ is an inflow rate and thus is added to the level, the loop is a positive one and hence reinforces the initial change In such case sign $\left(\frac{d\dot{x}}{dx}\right)$ is positive and will be negative if the polarity of the loop is negative, that is if the resulting change in the inflow rate is in the oposite direction to the change dx. If $\dot{x}$ is an outflow rate, all we have to do to extend the above definition for loop polarity is to attach a negative sign to the expression for $\dot{x}$, since variation in the same direction in the outflow, e.g in the death rate, and in the level, e.g. in the fish population means that the loop polarity is negative.

In order to identify irrigation systems’ resilience tipping points, that is the points where systems dynamics shift from an equilibrium behavior pattern to an exponential decay one, we propose a codified procedure to Richardson’s ideas based on a generalization of the simple stability test proposed by Ford [5: 54-55], and developed by Bueno [1].

The idea is to introduce a change in the system and watch how it reacts. The level variable is any stock in the model we wish to test. If the stock returns to the original value after the system is hit by an exogenous shock, the equilibrium is stable. On the contrary, if the stock moves farther and farther away from the equilibrium, the equilibrium is unstable. In the first case, we can say that the loop polarity of the feedback structure is negative while in the second case it is positive. Our conjecture is that the loss of resilience of irrigation systems can be seen as a bifurcation point where loop polarity changes from negative to positive sign .

The procedure is as follows:

1) Choose a variable of interest (x) that represents the resource users want to preserve and whose state they are able to assess.
2) Compute the ratio $\frac{d\dot{x}}{dx}$ for the observed conditions of the system and over a chosen reference time interval, attaching a negative sign to $\dot{x}$ if $\frac{dx}{dt}$ is an outflow rate
3) Choose a parameter that can vary $\frac{d\dot{x}}{dx}$. Use the parameter to vary that ratio until $\frac{d\dot{x}}{dx}$ changes sign in the reference time interval.

4) Compute the value of the variable of interest at the point where $\frac{d\dot{x}}{d\,x}$ changes sign and compare this value to the equilibrium value obtained in the last run before $\frac{d\dot{x}}{d\,x}$ shifts sign to identify the tipping point of the variable of interest which is inside this interval. The critical value of the variable of the interest assessed from the parameter chosen is the last equilibrium value before the sign shifts.

5) Repeat steps 2-4 for other parameters.

6) Select the largest of the critical value of the variable of interest obtained by steps 2-4 as the critical resilience level of the system and compare this to the actual observed level (or the simulated level at the actual observed conditions of the fishery); resilience degree is computed as:

$$\frac{observed\ level - critical\ resilience\ level}{critical\ resilience\ level} \text{ x } 100$$

IV. RESULTS

Assuming the variable of the interest is the irrigation infrastructure and performing calculations only for the parameter rain regime, Figure 3a shows that an irrigation system can lose sustainability due to small variations in environmental conditions. A reduction of 0.1% in the annual precipitation from year 20 to year 24 (35.2% drought → 35.3% drought) is enough to put the system on the collapse mode if it is operating close to its tipping point. In that mode, irrigators are unable to pay maintenance dues and, hence, maintenance falls below depreciation and the variable of interest – infrastructure – enter into a downward endogenous trajectory (Figure 3c).

It is noticed that between, say, years 25-45, unsustainable systems present a slowing down pattern before an abrupt change. This result – which indicates the tension among stabilizing (e.g., the stabilization loop) and amplifying (e.g., the death spiral) feedback loops working in tandem upon the system's dynamics near tipping points - has been identified as a universal property of systems approaching that threshold, and hence may be seen as an early warning signal of sustainability loss [14].

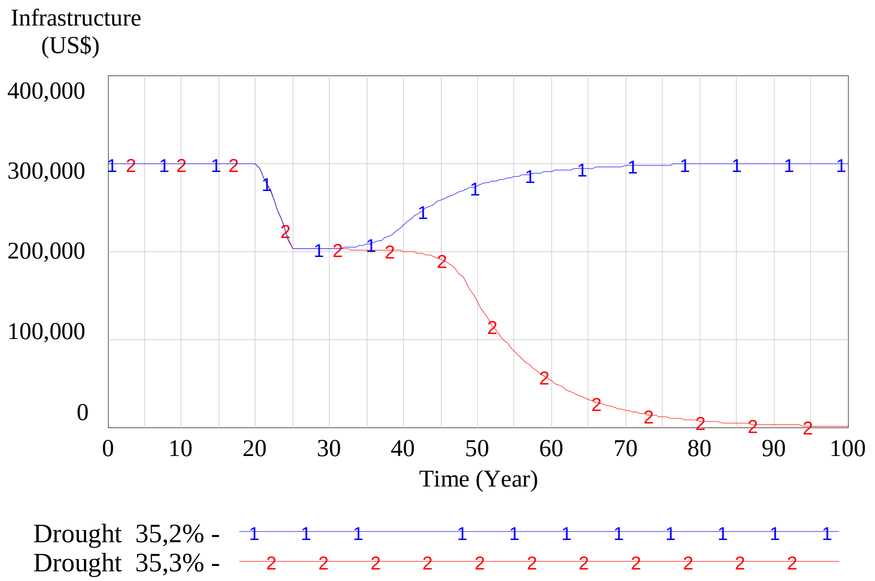
When the system is operating in collapse mode as in Figure 3e), the ratio $\frac{d\dot{x}}{dx}$ shifts from negative to positive in year 49, which allows to compute its resilience tipping point as indicated in step 6 above. This indicates infrastructure has started to deteriorate at an increasing rate, progressively moving away from its equilibrium value. When the system is operating in the equilibrium mode (Fig. 3d), on the other hand, the system's loop polarity shifts from positive to negative, indicating that the system will approach an equilibrium path afterwards.

As indicated in the Section I, the explanation of why the system displays an explosive behavior is that it becomes dominated by amplifying loops, as the death spiral in our basic model.

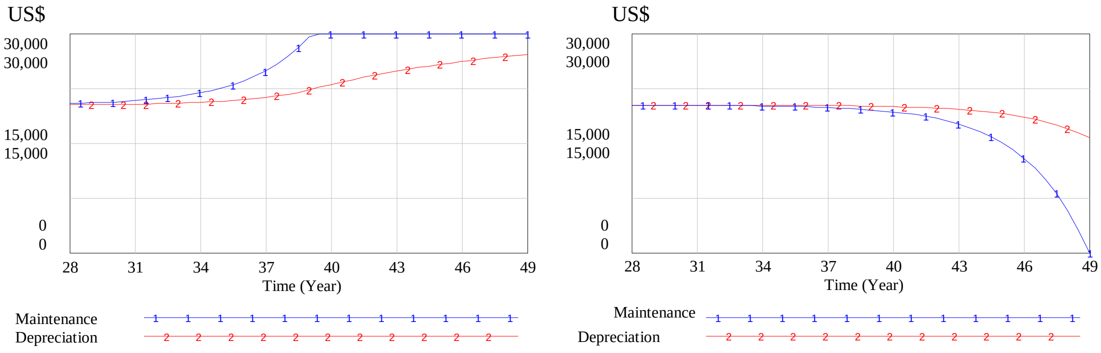
V. DISCUSSION

Simulations performed in Section III suggest that a major reason for the loss of sustainability of an irrigation system is the inability of farmers to perform O & M properly. At the system`s tipping point, i.e. at year 49, the infrastructure reaches the critical value in which profits equal household expenses: US$ 150,000. At this point, system´s resilience degree is zero, according the indicator calculated in step 6. Environmental shocks like droughts, henceforth, can lead irrigation systems to collapse by reducing the incomes of the irrigators below the level consistent with both maintenance dues and the payment of household expenses necessary for the survival of farmers and their families.

Now, imagine that after realizing that the system is on a collapse trajectory government decides to intervene, financing the total annual spending on maintenance costs in a particular year. It is easy to infer that if government acts timely by complementing private maintenance before the tipping point, say at year 47, the system will be able to recover relatively easily (Figure 4). But, if it postpones intervention even just for one or two years, the system will collapse, because it may already be dominated by the death spiral loop.

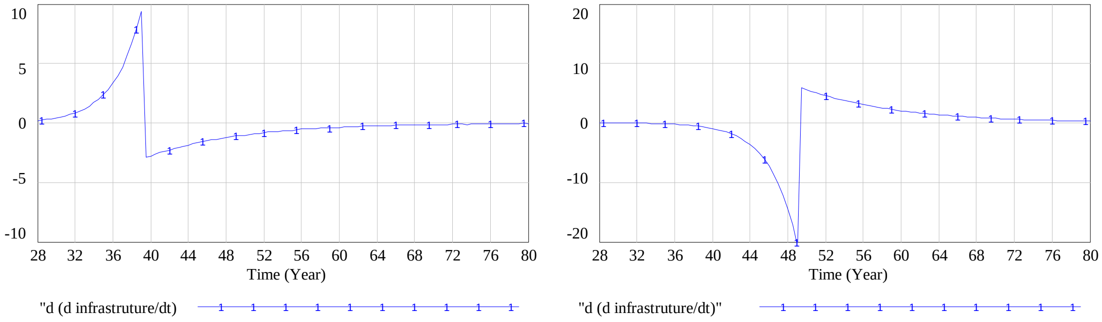


3a) Value of the infrastructure



3b) Drought 35,2%-.

3c) Drought 35,3%-.



3d) Drought 35,2%-.

3e) Drought 35,3%-.

Figure 3. Sustainable and unsustainable irrigation systems.

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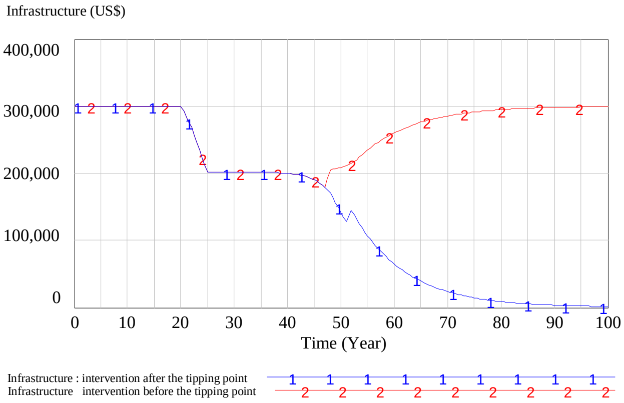

Figure 4. Leverage intervention points.

VI. CONCLUSION AND FUTURE WORK

Mostly because measurement or predictions of thresholds in socio-ecological systems (SESs) have low precision, the precise meaning of resilience and its identification still remain a subject of debate. This work has attempted to bridge that gap by providing a relatively simple procedure to assess resilience in a particular type of SESs - irrigation systems - based on loop dominance analysis. The proposed procedure uses changes in loop polarity from negative to positive as a signal of resilience loss. Specifically, it is shown that irrigation systems lose resilience when stabilizing (negative) feedback loops stop dominating dynamics forcing farmers´ income in a downward endogenous trajectory that impairs the ability of producers to carry out the necessary maintenance expenses. Hence, problems of maintenance of irrigation systems operating near tipping points can many times be explained by the inability of users to pay for maintenance of infrastructure and not by their refusal to pay the costs to maintain systems integrity. But can this approach (complemented by other techniques) help identify early signs of loss of resilience in order to enable government agencies to act timely to prevent the collapse of fragile irrigation systems?

Recent developments in the field of dynamical systems have suggested so. A number of generic symptoms may occur in a wide class of systems as they approach tipping points. One of those symptoms, which can indeed be considered as a universal property of systems approaching tipping points, is a phenomenon known in dynamical systems theory as critical slowing down [3]. Systems' dynamics in such case is dominated by a damped, driven effect created when positive and negative feedbacks operate in tandem. This implies that systems operating near tipping points become increasingly slow in recovering from small perturbations, due to the fact that amplifying (positive) feedbacks loops, such as the "death spiral", begin to offset the stabilizing effect of negative feedback loops as the stabilization loop in model presented in Figure 1, that is becoming less resilient in terms of this work [9]. Figure 4 depicts this characteristic slowing down process in action as an irrigation system approaches its tipping point: the later the system recovers original characteristics, the longer the return time to a sustainable exploitation path. Applied literature has tested a number of techniques to check whether the theoretically predicted critical slowing down may indeed be identified in actual complex systems, such as sensitivity and time series analyses. For instance, a way to test whether a system is slowing down is to interpret fluctuations in the state of the system as it responds to natural perturbations. Slowing down then should be reflected as a decrease in the rates of changing of the system near systems' tipping point (calculated by the approach proposed in this work), which may be measured by an increase in the short term correlation in key variables time series [7], such as farmer's income.

Unfortunately, there are signals that process is already taking place in several regions of the world. Growth in irrigation, mainly in arid countries in the Middle and Near East, has dramatically slowed over the last decades to a rate that is inadequate to keep up with the expanding food requirements. Besides, extensive areas of land in a number of countries have been degraded by waterlogging and salinization resulting of poor agricultural management and maintenance, which has resulted in major environmental disturbances and raised doubts about its very sustainability in many places in the world [12]. As a consequence of these problems, there will be probably fewer investments in new and existing irrigation projects in the future that have been made in the last decades, unless major improvements in the operation and maintenance of existing irrigation systems can bring those systems back to sustainable patterns of use, particularly in the world's poorest regions.

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